Thermoelectric Energy Harvesting with Carbon Nanotube Systems

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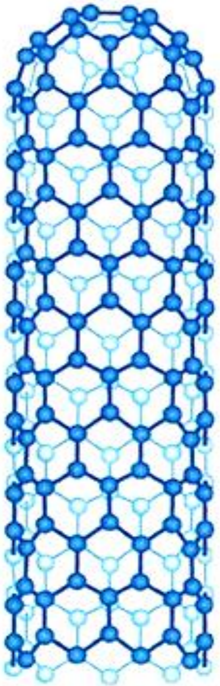
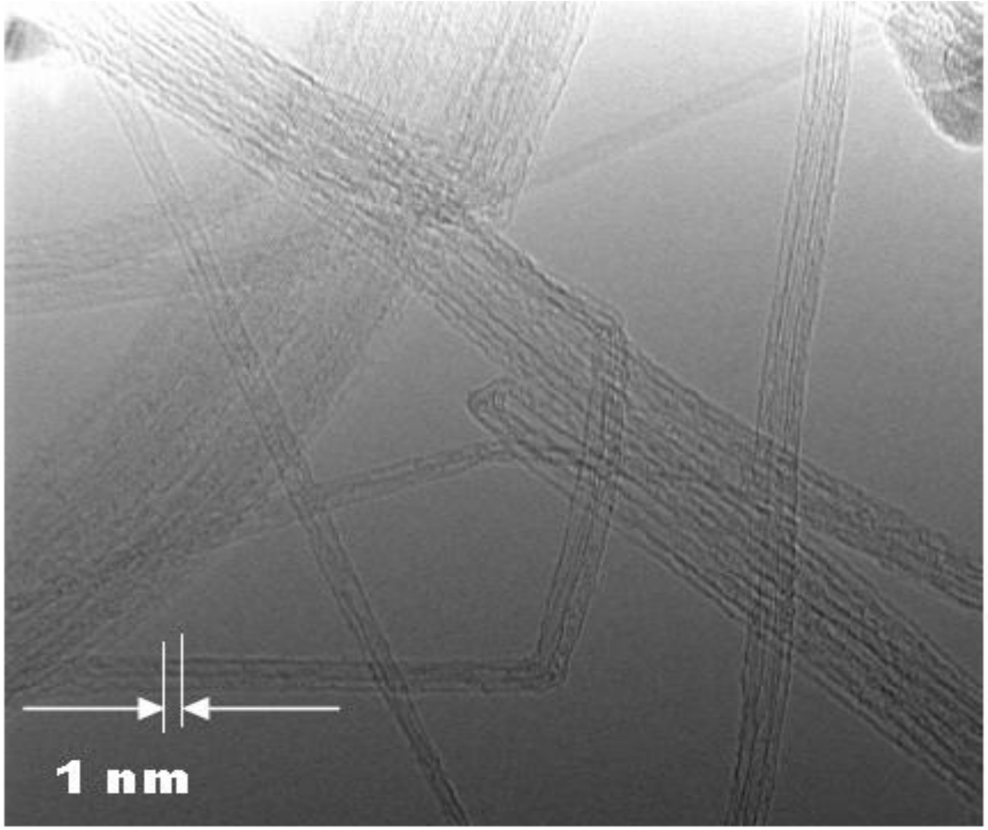
At the New England Nanomanufacturing Summit
at UMass Lowell, June 2010

Outline

- Carbon Nanotubes
  - Synthesis
  - Applications
- Energy
- Thermoelectrics
  - History
  - Physics
- CNT based Thermoelectrics
  - Material Progress
  - Fabrication Technologies

Carbon Nanotubes



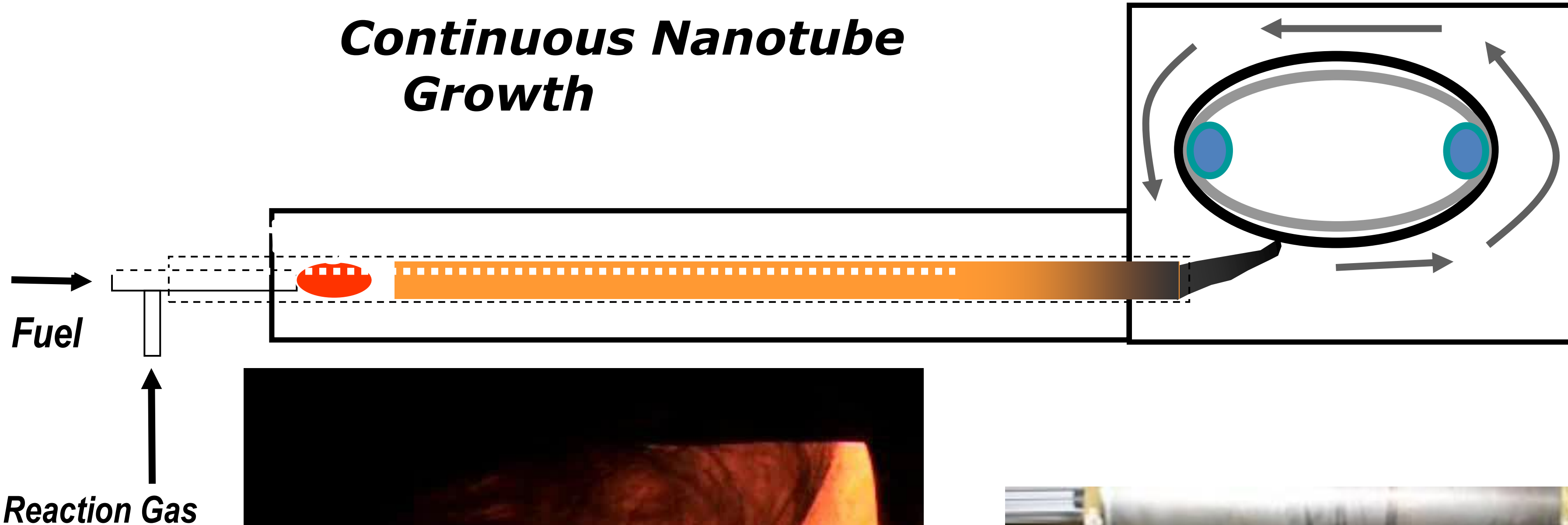


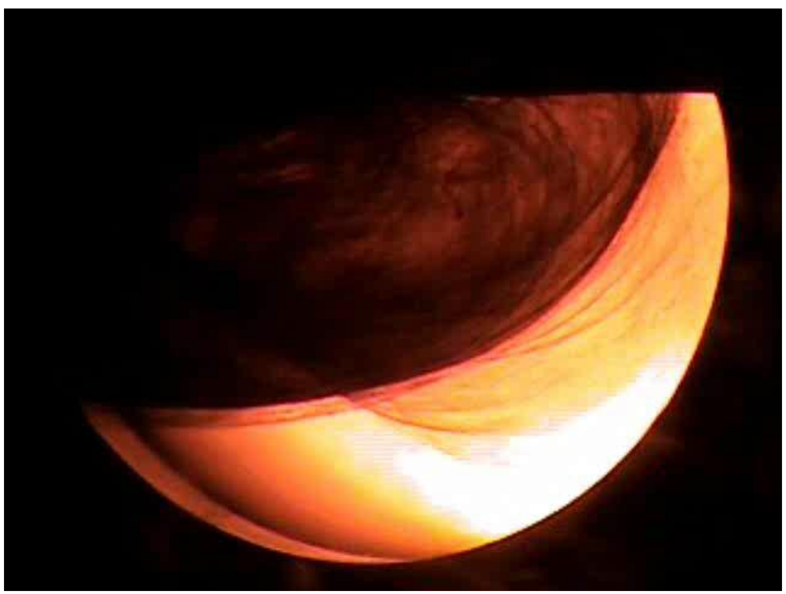
Smalley

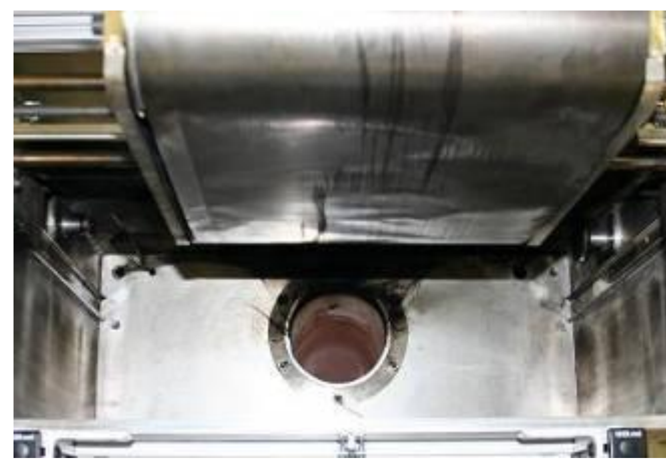
UNH

Synthesis

Continuous Nanotube Growth







Formats

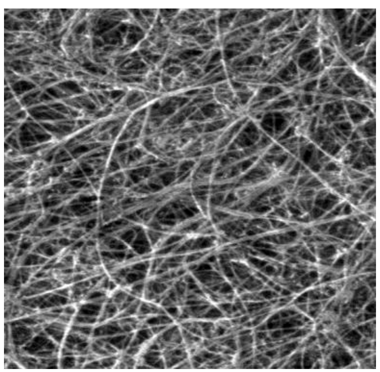
Sheet 132 cm by 234 cm

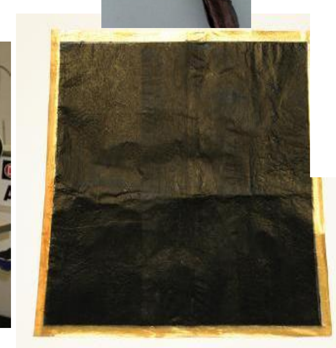
2 Kilometers of 4 ply Cable

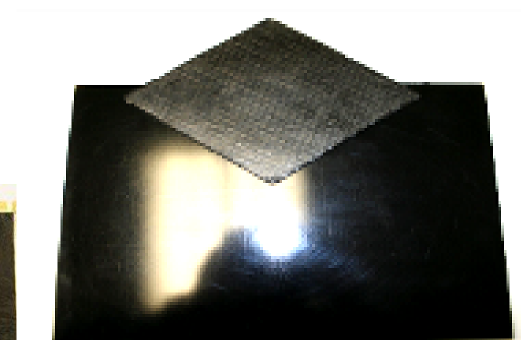
Safety of Articles

Products
DO NOT SHED

Confirmed by outside testing of lots of raw sheets and yarns to 1nm sensitivity.







No carcinogenic catalysts.

Products generally coated prior to shipping for increased handling safety.

Product Areas

Light-Weight Performance Materials:

Electrical Conductors

- EMI Shielding
- Antennas
- Data Cables
- Power Cables
- Windings
- Heaters
- De-icers

Structural Composites

- Pre-Preggs
- Armor

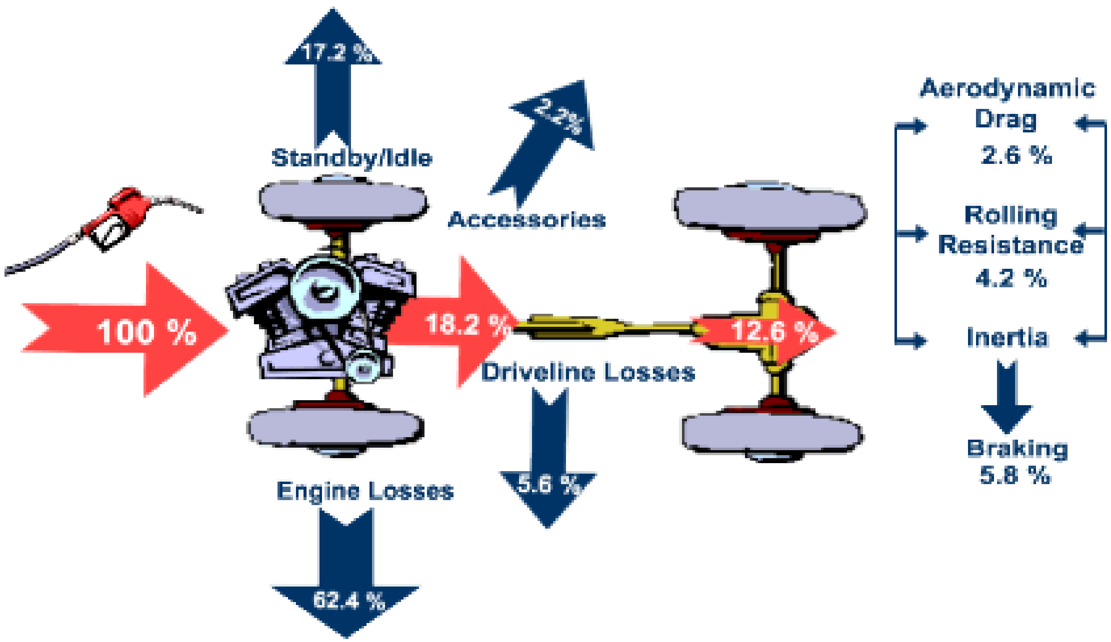
Thermal Management

- Heaters
- De-icers
- Heat Spreaders

Thermoelectrics

- Solar Thermoelectric
- Waste Heat

Waste Energy Availability

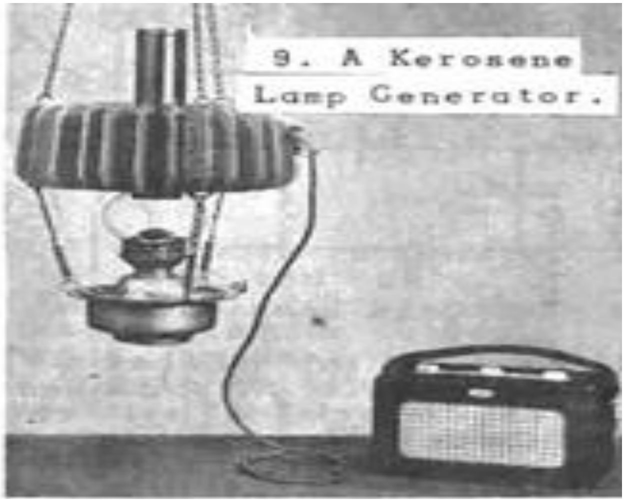


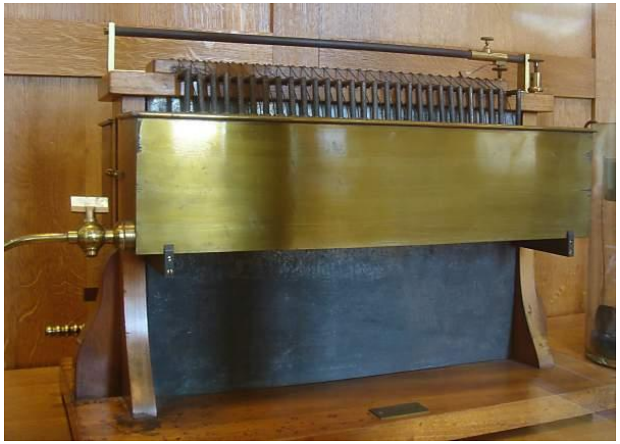
On average, 44% of fuel's energy is exhausted through radiator, a tens of kWs heat flux from ~90 °C to air temperature.

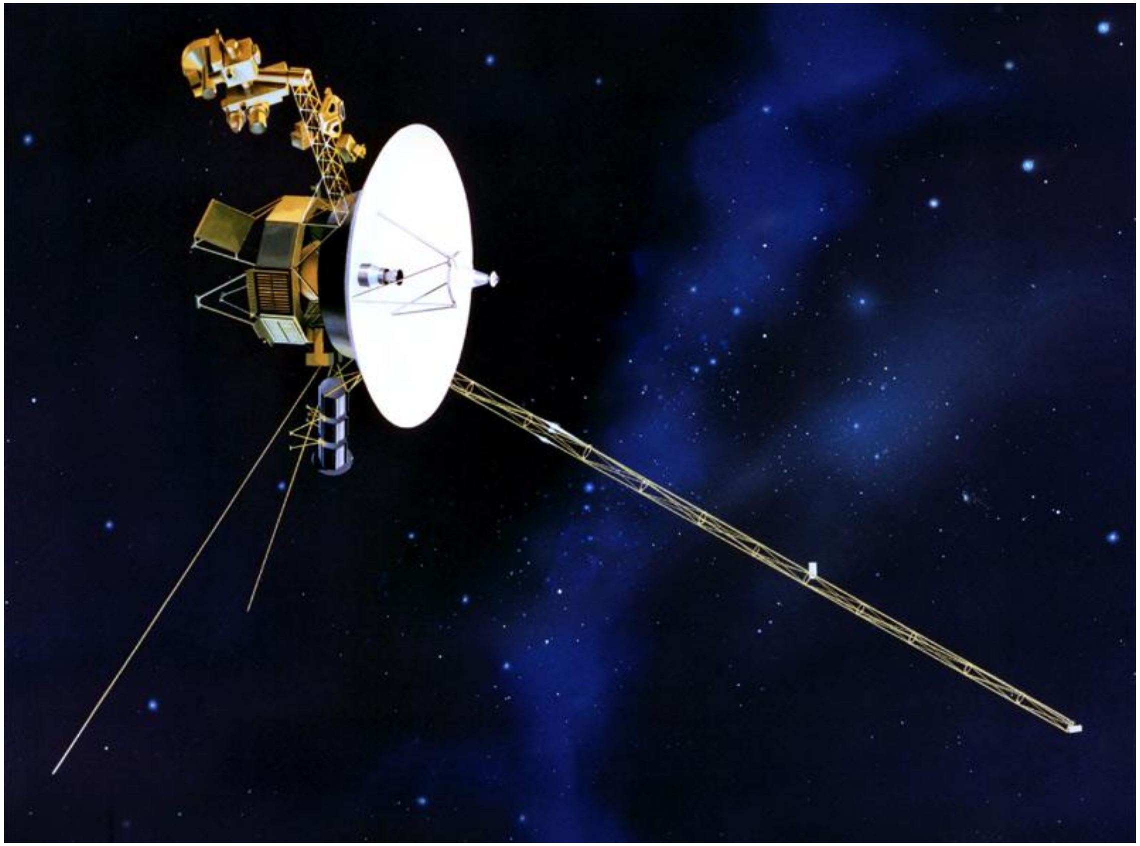
In the U.S. total loss equivalent to ~ 40 Billion Gallons per Year.

DOE

History of Thermoelectric Applications





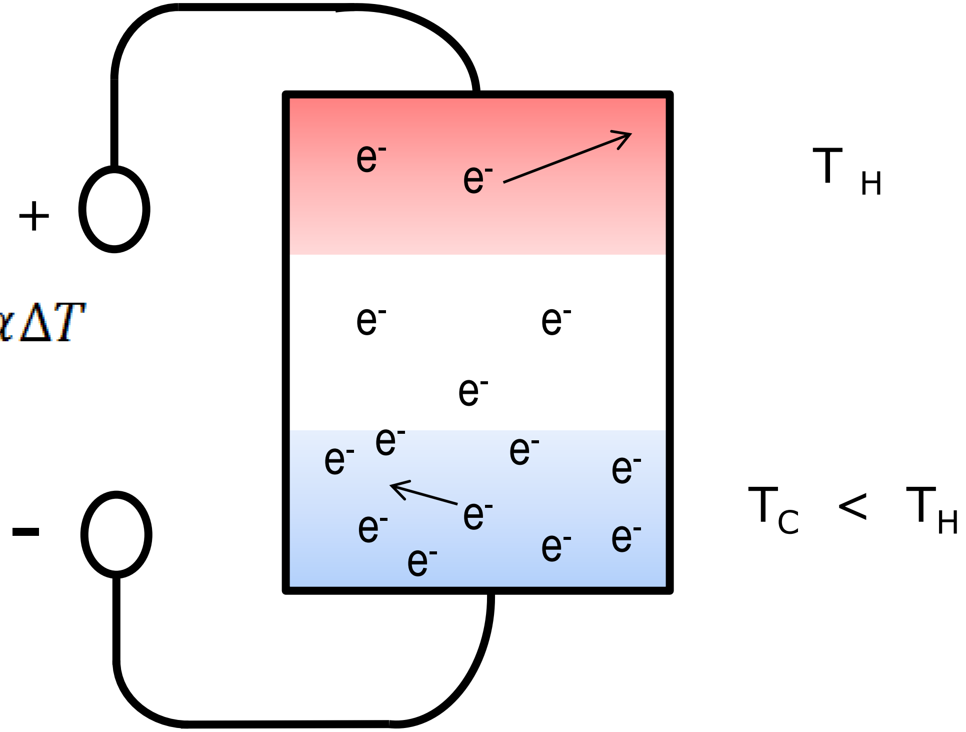


NASA

Thermoelectrics

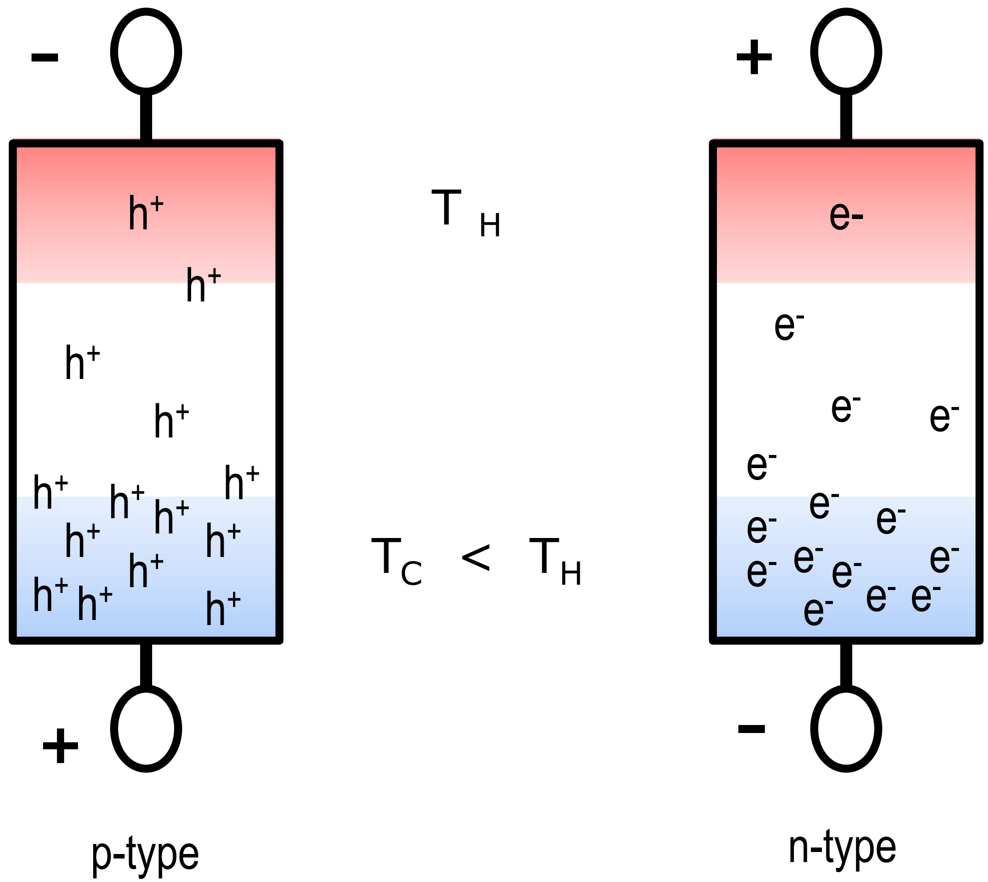
In 1826 T. J. Seebeck Discovered:

Voltage $V = \alpha \Delta T$

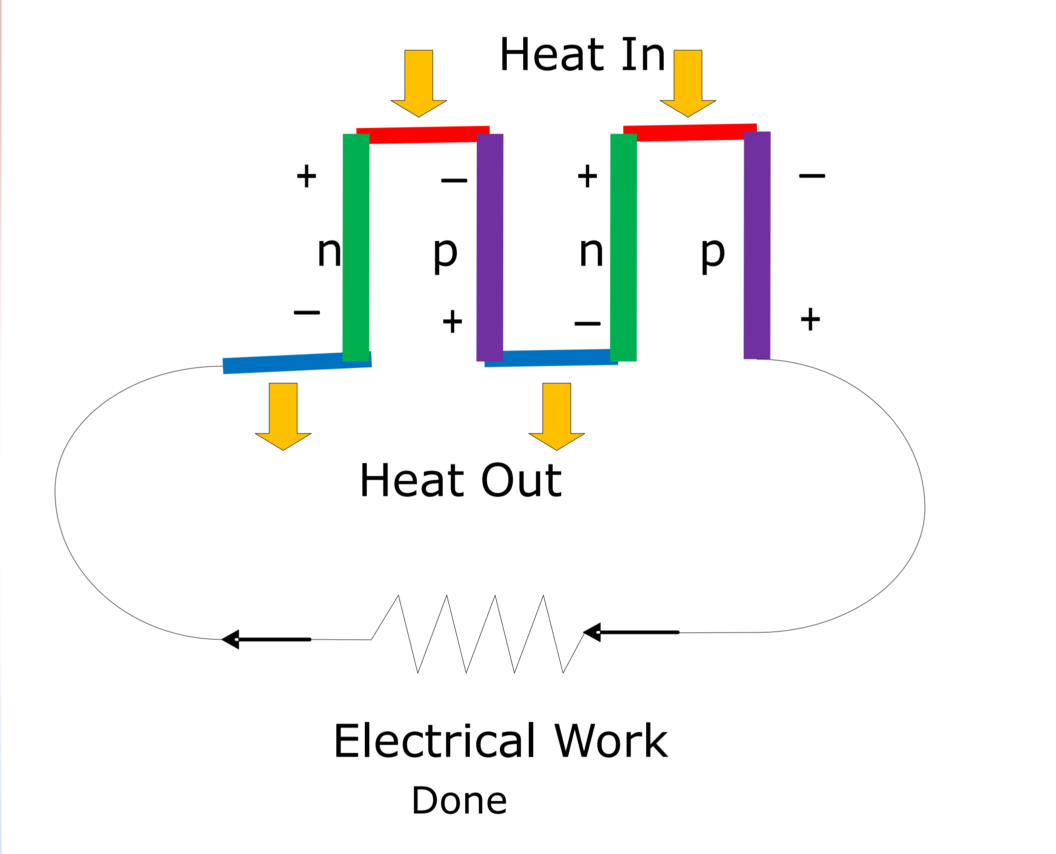


Thermoelectrics

p-type Semiconductors have opposite sign:



Power Generation



Generators: Commercial and NCTI CNT Experimental

Parameter	Value at ΔT of 200 K
Power / Mass	0.166 W/g
Power / Volume	0.665 W/cm^3
Dollars / Watt	$ 5 / W

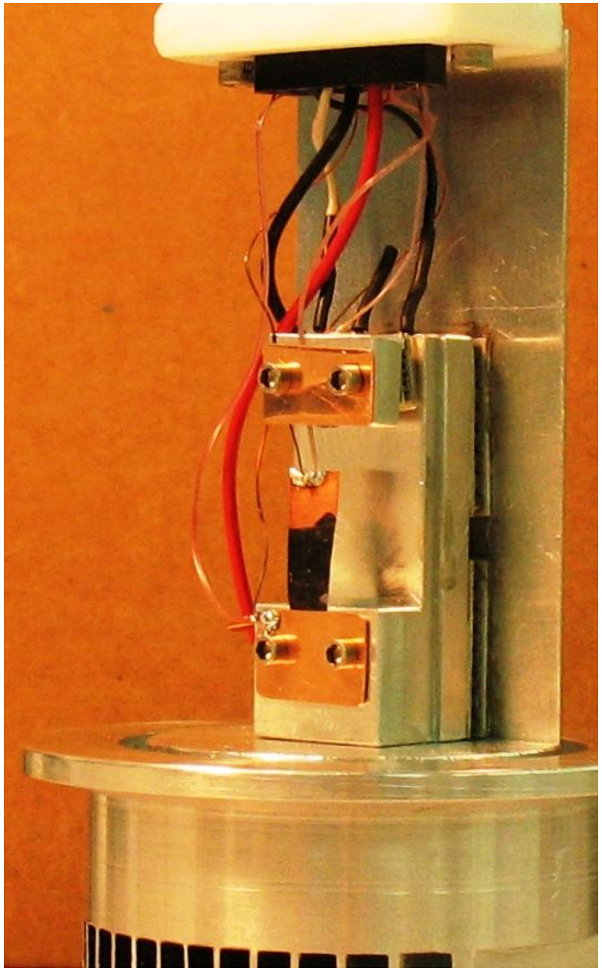
Parameter	Value at ΔT of 200 K
Power / Mass	0.060 W/g
Power / Volume	0.17 mW/cm^3
Dollars / Watt	$ 133 / W

Ranking of Thermoelectric Generators / Materials

Dimensionless Figure of Merit, ZT

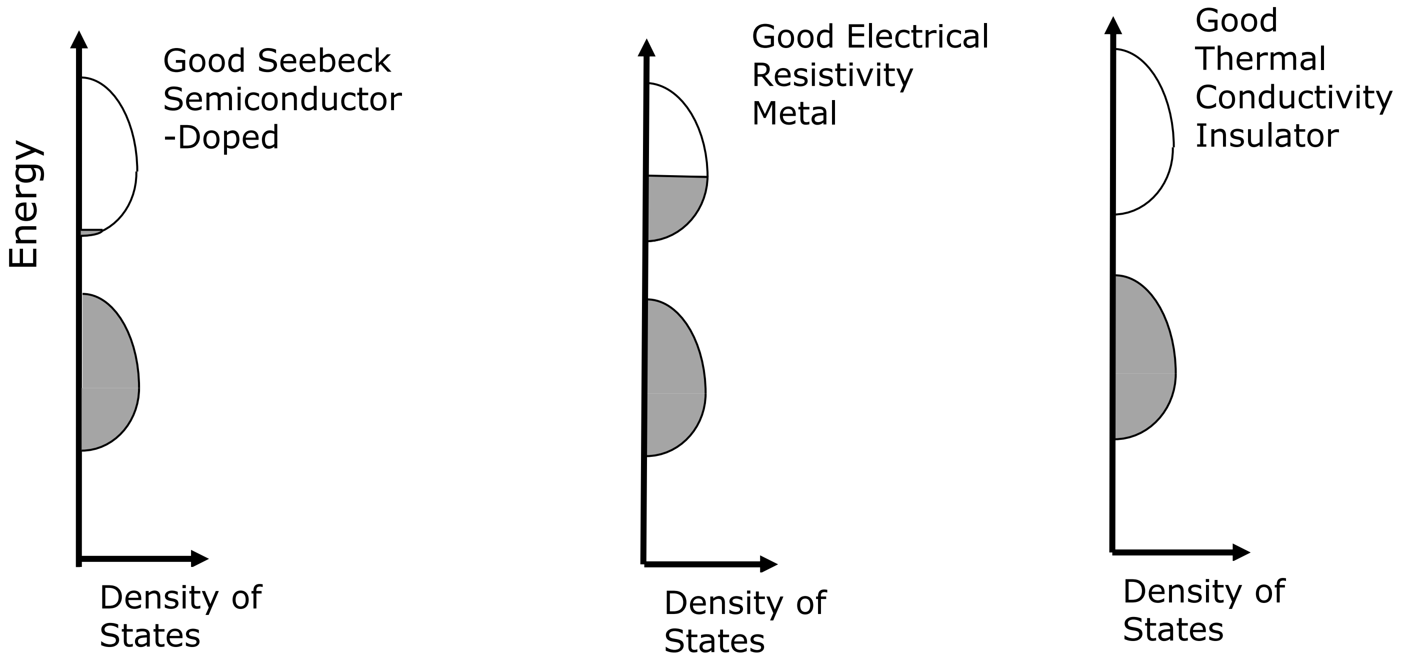
$$Z\bar{T} = \frac{\alpha^2 \bar{T}}{\rho\kappa}$$

- Power per Unit Weight
- Power per Unit Volume
- Power per Area
- Efficiency

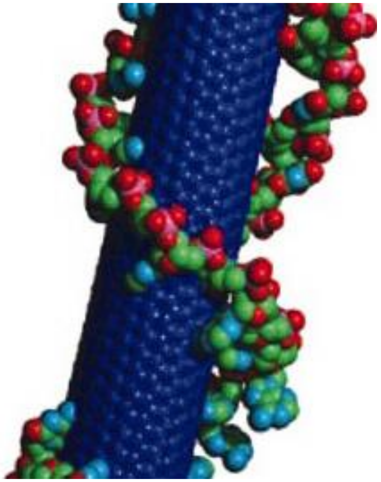


Electron Band Structure

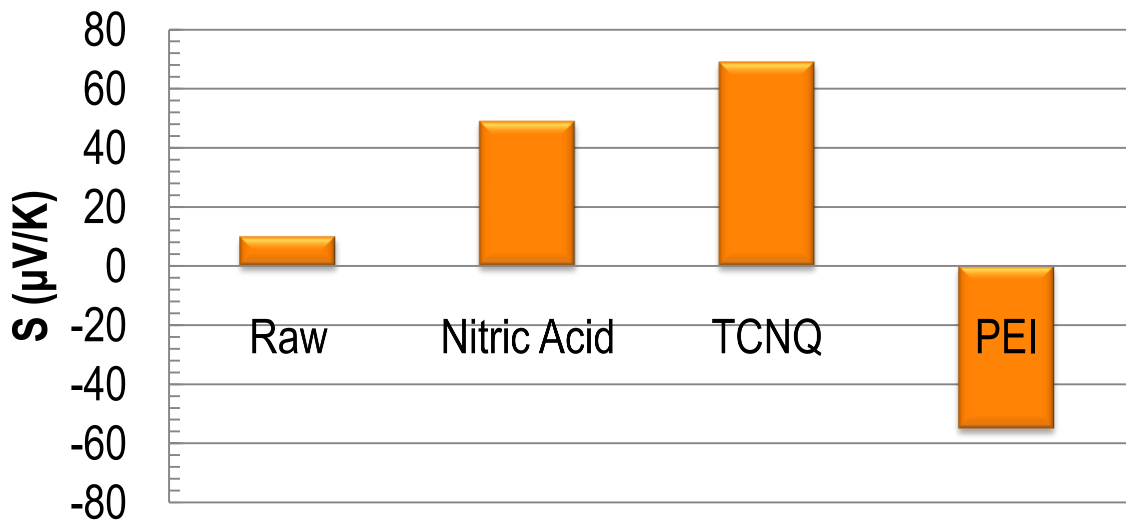
$$Z\bar{T} = \frac{\alpha^2 \bar{T}}{\rho\kappa}$$

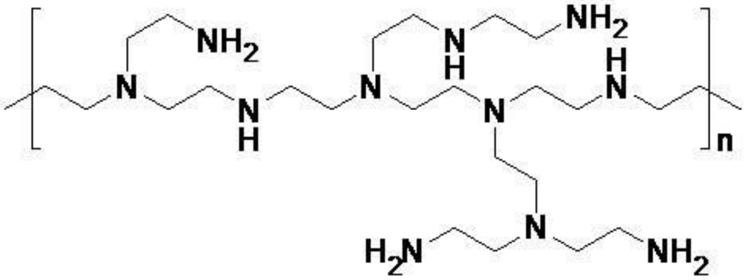


CNT Surface Doping – Charge Carriers

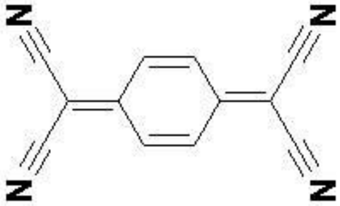


Dai



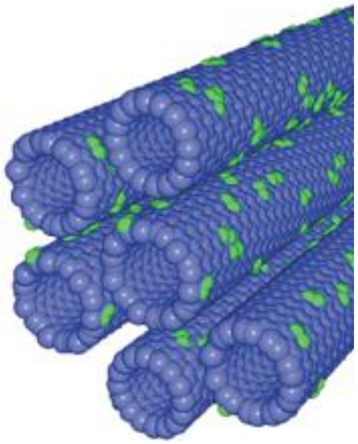


Polyethyleneimine (donor)

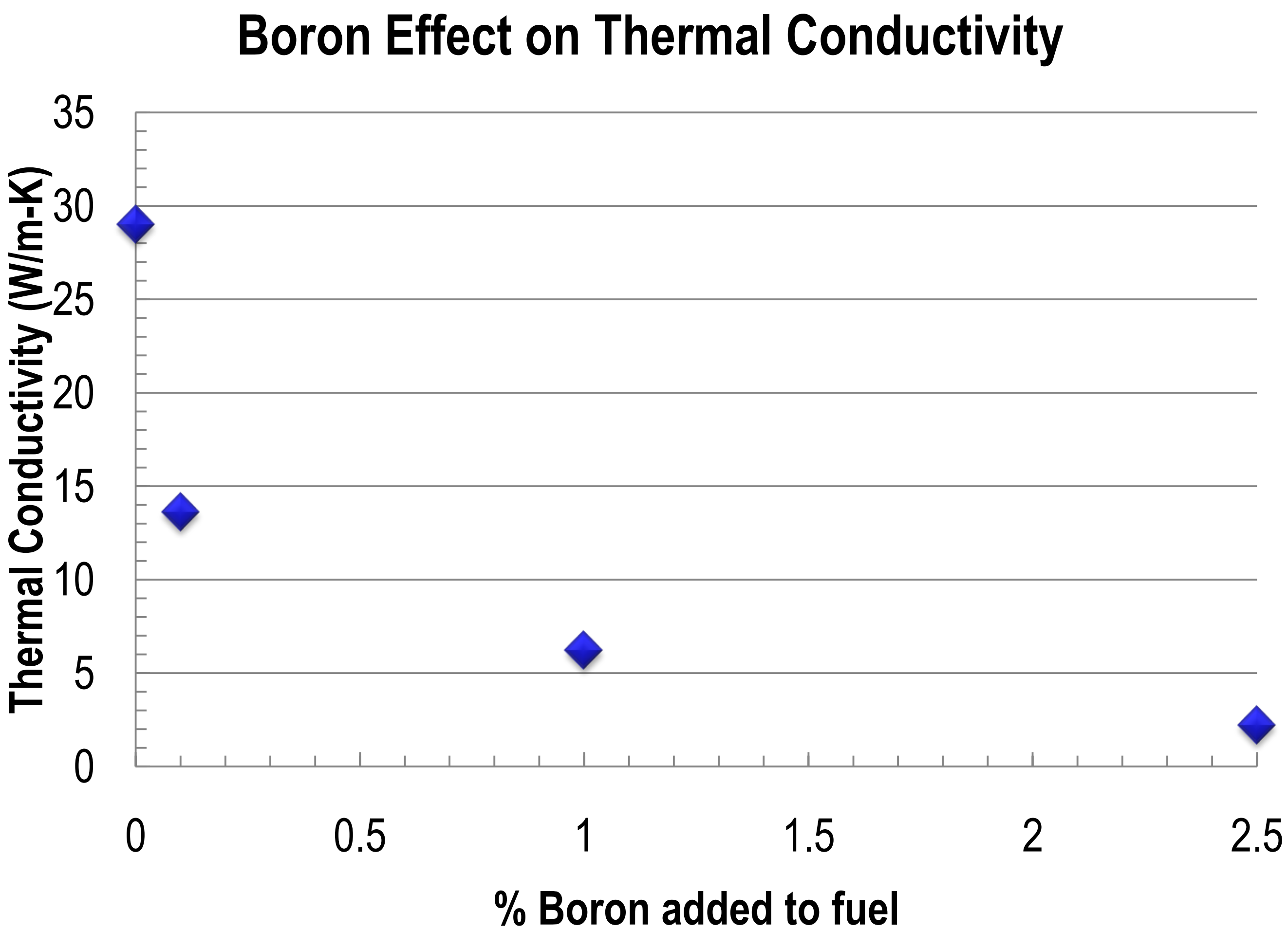


Tetracyanoquinodimethane (acceptor)

Substitution Doping -Phonon Scattering



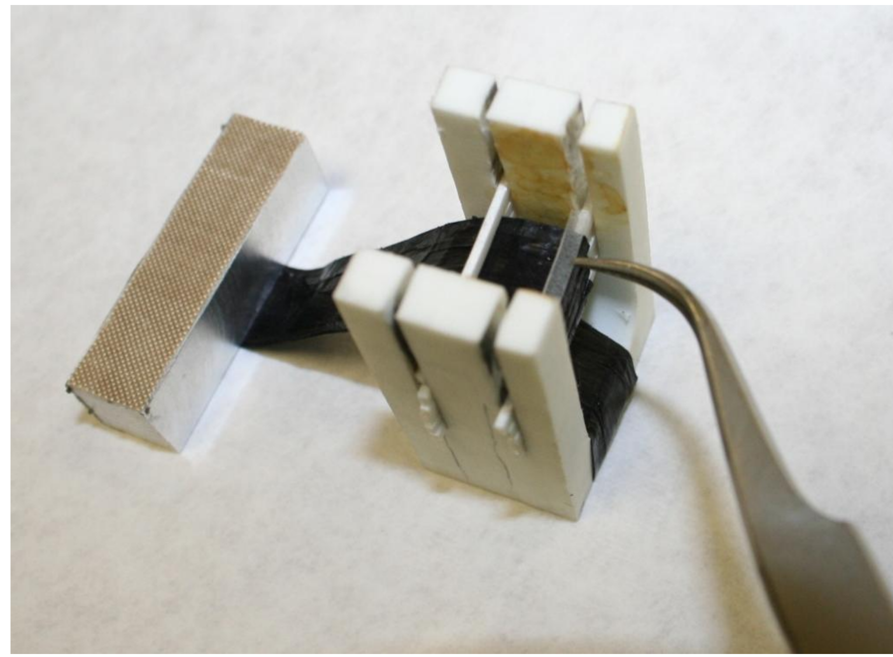
Zettl



ZT Results so far.

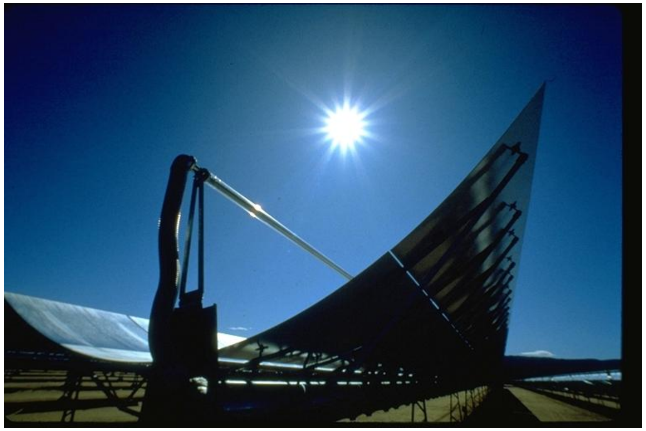
Parameter	Bi_2Te_3	CNT Felt	Units
Seebeck Coefficient	195	80	μV/K
Electrical Resistivity	1×10^{-5}	4×10^{-5}	Ωm
Thermal Conductivity	2	2	W/mK
ZT	0.60	0.011	none

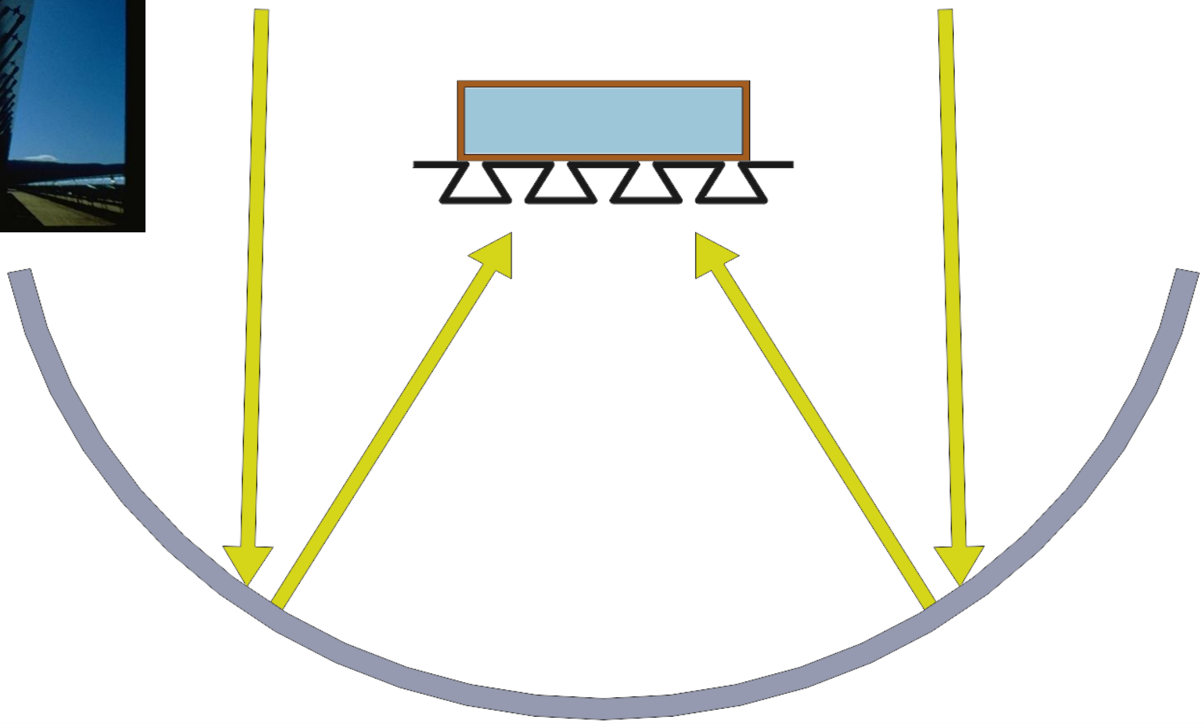
Print and Fold Technology



Self Supporting, Felt Only Thermoelectric Device

Deploy for Maximum ΔT





Results and Goals

Parameter $\Delta T = 200$ K	Commercially Available	CNT Current	CNT Target
Power / Mass	0.166 W/g	0.060 W/g	1.3 W/g
Power / Volume	0.665 W/cm^3	0.17 mW/cm^3	0.04 W/cm^3
Dollars / Watt	$ 5 / W	$133 / W	$1 / W
ZT	0.6	0.01	0.2

Conclusions

- Lots of waste energy and "low grade" heat is available to harvest.
- Wide dispersal of heat in space and time coupled with low conversion efficiency has in the past confined thermoelectrics to niche markets.
- Improved CNT materials can expand these opportunities.
- Carbon Nanotube based Thermoelectrics may be competitive in applications very sensitive to power to weight.
- Printing and folding fabrication of abundant raw material means price can be competitive with semiconductor technologies, if CNT manufacturing becomes large scale.
- Significant improvements in electrical conductivity and Seebeck coefficient are an object of our research at Nanocomp